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We have completed a towed electromagnetic survey, mapping the electrical resistivity of the seafloor across an area of the Californian continental shelf off Humboldt Bay. Over 120 km of tow-lines were completed, measuring resistivity profiles to 20 m depth continuously along track from water depths of 100 m to around 30 m. Our data show a high degree of variability in porosity structure along the shelf and we identify three distinct environments based on the resistivities recorded and the porosities inferred from them.

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The Shallow Porosity Structure of Shelf Sediments off Humboldt Bay, Northern California: A Towed Electromagnetic Survey.

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Long Term Goals:

Maps of sedimentary physical properties are essential to a complete picture of stratigraphy throughout the littoral zone, and provide valuable constraints on the processes responsible for shaping the modern day shelf. Providing such maps on the scales relevant to recent depositional processes is hard, if not impossible, using conventional geophysical and sampling techniques. Measurements of electrical resistivity -a property closely related to porosity- are entirely feasible on a length scale of 10s of meters both horizontally and with depth, and covering large areas of the shelf, although there is currently only one system available that can do this. We aim to make electrical resistivity measurements a routine component of shallow geophysical surveys of sedimentary properties and to demonstrate the usefulness of resistivity as a tool for understanding facies conditions.

Scientific Objectives:

To carry out an electromagnetic survey of the Californian convergent margin, mapping the electrical structure over the top 20m or so of sediments, using the towed EM system developed by Dr. Law at the Pacific Geoscience Centre. To interpret these resistivity measurements in terms of the porosity structure of the shelf and the depositional processes responsible for the observed structures.

Background:

The motivation for using EM methods to map the seafloor arises from a strong dependence between the amount and distribution of seawater in the sediments and the bulk resistivity structure. Over sedimentary sequences resistivity is a particularly useful parameter as it can be easily related to porosity and, from there, to grain size and texture. If resistivity is mapped over a region of interest, then this map can be used to identify facies boundaries, and together with seismic velocity, reflection profiles and sediment cores provides a powerful technique to unravel the processes that shape the preserved stratigraphy.

Seafloor EM techniques rely on the skin depth, or the length scale over which EM fields decay in a conductive medium. In general, the seafloor is usually more resistive than seawater, and is therefore characterized by longer skin depths. This means that when a source and receiver, which are both close to the seafloor, are separated by a lateral distance greater than a few skin depths in the ocean, a received signal will be dominated by the fields that have propagated through the seafloor, the signal in the seawater having been attenuated. Standard resistivity techniques do not have good sensitivity to the seafloor structure because at D.C. far more current flows in the seawater than enters the seafloor. Mapping shallow sedimentary features requires frequencies of a few kHz and source-receiver separations of 10-50m. Measurements of the amplitude and phase of the magnetic field generated by the source can be modeled in terms of an apparent resistivity, which is the resistivity of the uniform half-space which would produce the observed response. It is also possible to take a series of readings from different receivers at one station and invert these values for true porosity as a function of depth. Information from seismic reflection profiles and sediment cores on the depths to morphological boundaries and local grain size provide important tie points for the inversion.

Approach:

The technique we used to measure the shelf resistivity structure this summer provides a means of mapping porosities with superior spatial coverage than conventional coring techniques, can measure porosities in regions where coring techniques fail to recover samples, and also provides estimates of physical properties where seismic reflection profiles are contaminated by strong bottom multiples or the presence of biogenic gas.

The system used for the survey is operated by the Geological Survey Of Canada and was designed by Dr. Lawrie Law. The system forms an array on the seafloor of about 50m in length, and has a source and three receivers at separations of 4m, 13m and 40m. Both source and receivers are horizontal magnetic dipoles, the system operates in the frequency domain, and is dragged on bottom to ensure optimal coupling to the seafloor. A heavy depressor unit at the front of the array keeps the system on bottom and also contains a CTD sensor package. The longest offset receiver is more heavily influenced by deeper structure than is the closest receiver, which measures the porosity of the near surface sediment layer. A set of measurements consists of logging amplitude and phase at each of the three receivers at three distinct frequencies, and takes on the order of 20 seconds, or approximately every 10 meters to complete (at 2 knots). The system uses less than 1 kilowatt of power and can be deployed from most coastal size ships: the source weighs about 100kg, while the depressor weight, which keeps the system on the bottom, weighs about 250kg. The receivers are deployed by hand. Communication between the seafloor components of the system is through fiber optic link and the data are logged on board ship in real time via a modem link down the 4-conductor cable which tows the system.

As the system is towed along the seafloor, it produces a series of apparent resistivities at intervals along the tow-line. Each apparent resistivity is in some sense an average of the resistivity over a local volume surrounding the source and receiver. By examining the apparent resistivities along track, as well as those between the three source-receiver pairs, it is possible to construct a map of the seafloor resistivity versus depth and to relate this to porosity changes and to structural features.

Accomplishments and Results:

In August we completed a 5 day cruise on board the R/V McGaw, sailing from Eureka, California. We completed over 120km of track-line across the shelf, from water depths of 30m to 100m. Our lines are coincident with high resolution seismic reflection surveys made previously by the U.S.G.S. using the HUNTEC system. High resolution bathymetry and side-scan data for the entire region were also available. The data we collected immediately allow us to identify three distinct depositional environments on the shelf, based on analysis of apparent porosity data and sample inversions for true resistivity as a function of depth.

The first region, to the northwest of the entrance to Humboldt Bay, occurs between water depths of about 65-75m and 100m and is characterised by a thin, moderately high porosity (~55%) surface layer which overlies a less porous and homogeneous substrate. In waters shallower than 65m, the upper layer decreases in apparent porosity and the underlying layer becomes less homogeneous. The apparent porosities measured on the 13m and 40m receivers are essentially the same, indicating that there is little or no porosity gradient beneath the top 2m or so. This point is emphasised by an inversion of data at a point along this track within zone 1 which shows a uniform substrate resistivity. In general the thickness and resistivity of the upper layer decreases towards the shore line.

The second regime occurs on the inner shelf at water depths less than 60m and between $40^{o}49'$N and $40^{o}54'$N. Here, we see high spatial variability in porosity structure, with apparent porosities less than 20%, in some places as low as 10%. These values might not be remarkable in a hard rock environment, but are astonishing in a shelf sedimentary context. There are several possible explanations for the low apparent porosities. Upwelling fresh water channelled to the seafloor through local fault and anticline systems is one possible explanation. Another, which has more support from other observations in the region, is that a significant volume of natural gas is present beneath and may have seeped through the seafloor at this location over time. The gas present within the sediment could be responsible for the raised resistivities, but this would probably require a high volume fraction. A continuous process of carbonate precipitation through oxidisation of methane near the seafloor could build a substantial thickness of lithified material if sedimentary deposition buries each layer of carbonates, raises the oxic layer, and causes a new cycle of carbonate deposition on top of the old. This lithification could satisfactorily explain the high resistivities as it would cause substantial reductions in permeability.

The third regime begins about 5km to the north of the Humboldt Bay entrance as a coast-parallel band a few kilometers wide. Opposite the Bay entrance the region widens and extends in a south-westerly direction, at least to water depths of 100m. Data collected through out this region are characterised by the furthest receiver recording higher apparent porosities than the intermediate receiver. This implies the presence of a buried layer of low porosity sandwiched between high porosity upper and lower units. For

this to happen, the intermediate low porosity zone probably acts as a permeability boundary preventing the de-watering of the buried substrate. The limits of this region are roughly coincident with the swath of low backscatter observed by Goff et al. which they associate with the Eel river delta.

The data described are currently under analysis. We have modified inversion codes that find optimally smooth layered models satisfying the data to run on a unix platform. Our intention is to obtain layered models below each measurement point surveyed and to stitch these models together to form profiles of resistivity versus depth. These resistivities can then be interpreted in terms of porosity and in terms of their causative geology and depositional processes.

Scientific Impact:
We have collected the largest data set ever of shelf sedimentary electrical resistivities. Our data provide a new insight into the structure across the Californian STRATAFORM area and have identified depositional environments based on their distinct resistivity-depth profiles. One of these environments is particularly unusual and may indicate carbonate deposition occurring on a scale not seen before in a shelf environment.

Recent Publications Supported by ONR:

Evans R.L., L.K. Law, B. St Louis, S. Cheesman and K. Sananikone, The Shallow Porosity Structure of the Continental Shelf off Humboldt Bay, California: Results of a Towed Electromagnetic Survey, submitted to Marine Geology, 1997.